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DEVELOPMENT OF HIGH TEMPERATURE THERMAL REACTORS IN GERMANY

by

R. HECKER, W. RAUSCH and R. SCHULTEN

1967

THTR 32

Report prepared at KFA
Kernforschungsanlage Jülich des Landes Nordrhein-Westfalen e.V.
Jülich, Germany

Association No. 003-63-1 RGAD

Paper presented at the Nuclear Energy Meeting 1966,
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— The work for the development of gas turbines for use with high temperature reactors reached a point where tenders have been submitted for a 25 MWe closed-cycle gas turbine prototype plant ;
— The THTR-Project for the development of a 300 MWe prototype reactor representative of full-scale power plants up to 1200 MWe shall provide final design documents by the end of 1967.

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SUMMARY

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Development of High Temperature Thermal Reactors in Germany (x)

I. Introduction

It is now little more than 10 years ago that a group of physicists and engineers started work on the development of High Temperature Gas-Cooled Reactors in Germany. Even at this very early stage their concept differed considerably from the ideas of other groups: the core was not to consist of prismatic fuel elements as in most other reactors; instead it was to be made up of a pebble-bed of individual mobile fuel balls. This meant that the advantages of both a heterogeneous and a homogeneous core could be combined by the adoption of differential fuel elements, namely

- fuel elements, the reactivity of which is small compared to that of the total reactor, and
- the dimensions of which are so small that burn-up variations in individual fuel elements are neglegible.

The advantages of this concept are very obvious:

- the exchange of fuel elements can be performed under all operating conditions;
- optimum burn-up can be achieved for each differential fraction of the fuel by continuous burn-up control;
- the mechanical integrity of the fuel elements can be determined regularly, and
- no excess reactivity is needed to compensate burn-up with the consequence of lower fuel inventory and better neutron economy.

(x) Manuscript received on April 12, 1967.

The idea was fascinating, but the work taken up by the BROWN BOVERI/KRUPP Reaktorbau GmbH. for the realisation of this idea was not an easy one: to start a new line of power reactors in a country where experience in reactor development was close to zero at that time.

In 1958 a group of utility companies, now united as ARBEITSGEMEINSCHAFT VERSUCHSREAKTOR GmbH. - AVR - became interested in the project and at the end of 1959 a decision was taken for the construction of a 15 MWe Experimental Power Station, the AVR Reactor. This first power reactor to be developed entirely in Germany became critical for the first time on August 26, 1966, and is now being prepared for operation under power.

A direct consequence of the work being done for the development and construction of the AVR Reactor is the Thorium High Temperature Reactor Project - THTR - which unites EURATOM, the KERNFORSCHUNGSANLAGE JÜLICH des Landes Nordrhein-Westfalen e.V., and BROWN BOVERI/KRUPP Reaktorbau GmbH. in a common effort to extend the pebble-bed concept to a full scale power reactor prototype. By the end of next year design documents for a 300 MWe THTR will be completed with sufficient information to permit extrapolation to plant sizes up to 1200 MWe.

The idea to use gas-turbines in conjunction with high temperature reactors is as old as the idea of the high temperature reactor itself - this for the very simple reason that sufficiently high gas temperatures for the economic operation of gas turbines are available with these reactors. In the past few years, GUTEHOFFNUNGSHÜTTE STERKRADE AG. - GHH - was engaged in several studies on the combination of gas-cooled high temperature reactors and gas turbines. At present, GHH has finished project work for a 25 MWe closed-cycle-gas turbine prototype plant using a helium cooled high temperature reactor with prismatic fuel elements.

In Part II of this paper a survey will be given of the actual state of these three high temperature reactor projects currently being under development in Germany. In Part III the economical aspects will be presented and an outlook will be given on further possibilities with special regard to the potential for high conversion factors, and, ultimately, breeding.

II. Actual State of HTGR Development

A. The AVR Project

The main purpose of the AVR power plant which has been built by Brown Boveri/Krupp in Jülich was:

- to yield design, construction, and operating experience for high temperature reactors;
- to prove the feasibility and the special merits of the pebble-bed concept;
- to test different pebble-type fuel elements;

and in this way

- to serve as a tool for the future development of high temperature thermal reactors in Germany.

The general reactor arrangement is shown in Figure 1 which demonstrates one of the particular features of the AVR reactor, the integrated design. The entire primary circuit including steam generators, circulators, gas ducting, and flow control mechanism is accomodated inside a common pressure vessel. Today, nearly all known gas-cooled reactor projects have adopted the integrated design: a confirmation that Brown Boveri/Krupp's decision of 1958 was the right extrapolation to the future.

The general lay-out data of the AVR reactor are given in Table I.

Table I

General Lay-out Data of the AVR Reactor

Electric Power	15 MW
Thermal Power	46 MW
Average Power Density	2.2 MW/m^3
Core Diameter	3 m
Average Core Height	3 m
Fuel Element Diameter	60 mm
Number of Fuel Elements	100,000
Maximum Power per Element	2.4 kW
Number of Absorber Rods	4
Cooling Gas Pressure	10 atm (a)
Primary Circuit Pressure Drop	0.065 atm
Blower Power	2 x 58 kW
Core Inlet Temperature	175 °C
Core Outlet Temperature	850 °C
Steam Conditions:	
Temperature at Turbine	500 °C
Pressure at Turbine	71 atm (a)

The safety of the whole system is mainly determined by its capability to prevent fission products from escaping out of controlled areas. Originally, before fission product retaining fuel was available the inner pressure vessel of the AVR reactor was considered a barrier for gaseous activity. This vessel which has various penetrations for equipment, was leak controlled by a second container surrounding the inner one completely and forming an interspace as controllable area.

Since in the actual design coated particles are used in the fuel elements, the outer pressure vessel and the sealing gas interspace are much less important for the safety and can be considered as a large additional safety margin.

The design features of the reactor system place very specific requirements on the spherical fuel elements. The dominating specifications are:

(a) Irradiation stability to less than 3 % dimensional changes;

(b) High thermal conductivity to avoid excessive temperature gradients in the element;

(c) Impact resistance to drops from 4 m high on a pebble-bed combined with abrasion resistance;

(d) Limited oxidation rate in the presence of certain impurities contained in the cooling gas; and

(e) A release to birth rate (R/B value) of less than 5×10^{-4} for Xe-133 after a burn-up of 4 % fifa.

Figure 2 shows a section of the AVR fuel elements.

Comparison of various manufacturing techniques for the fuel element led to the design of a hollow graphite shell of 60 mm diameter with a wall thickness of 10 mm. This shell contains a graphite matrix with uniformly dispersed coated particle fuel and is closed by a threaded plug.

Contrary to reactors with prismatic fuel elements the pebble-bed concept is suited to avoid any fuel-handling machinery inside the core. Gravity is made use of for the extraction of fuel elements and pneumatic energy with the coolant as transfer medium for the loading of recirculated or new elements. Thus, only pipes are required inside the pressure vessel, the necessary components for handling operations as for example singulizer, scrap-separator, burn-up measuring device and pneumatic elevator being located in accessible areas.

The following functions have to be fulfilled by the fuel handling system:

1. Loading of new fuel elements to keep the reactor critical at the predetermined average core temperature. At full power less than three new fuel elements per hour are necessary to compensate burn-up in the core.

2. Unloading of unfueled or depleted spheres to control the core height. The spheres are selected for extraction by a γ-activity detector to discriminate between fueled and unfueled balls and a neutron absorption measurement for the determination of burn-up.

3. To achieve a flat characteristic of coolant temperature at the core surface a definite distribution of fuel in two radial zones has to be established. This can be done by simply varying the ratio of fueled balls of different burn-up to be loaded by the central or one of the four peripheric charge tubes.

Practical experience has proved that in spite of the ideal shape of a spherical fuel element particular requirements have to be met in respect to its handling.

One of the unexpected effects that arose was the tendency of the pebble-bed core to orientate if circulated close to a flat wall. This "crystallization effect" is shown in Fig. 3. After circulation of some 500,000 spheres in a perspex model a systematic and almost densest packing formed in the outermost layers close to the core-wall. As the velocity profile over the cross section of the core is severely influenced by this effect it had to be prevented. Fig. 4 shows the grooves that were machined into the graphite wall of the AVR core and by which the orientation of spheres was completely eliminated.

The overall negative temperature coefficient in conjunction with the size of the AVR reactor core and the possibility of controlling reactor power by circulator speed simplifies the problems of reactor control considerably.

The four absorber rods which are installed in special graphite "noses" protruding into the pebble-bed core are only needed for start-up and shut-down purposes and for emergency conditions.

The start-up experiments for the AVR reactor began on July 14, 1966, with the loading of the first fuel element. Due to a number of unsatisfactory valves in the helium system these experiments were performed under a nitrogen atmosphere. The build-up of the critical core configuration was continuously controlled by simultaneous experiments in a scaled-down model. Rechecks on the ratio of fueled to unfueled elements at the core outlet showed surprisingly well agreement with predictions. Criticality was achieved about six weeks later on August 26, 1966. The great number of zero-energy experiments that followed gave first valuable information on the physical and technical behavior of a pebble-bed reactor. The critical experiment itself made possible a better evaluation of the different effects that could not be taken proper account of in early calculations, and which will furnish a checkpoint for further calculational methods.

The temperature coefficient was determined in the range from 25 to 100 °C in excellent agreement with calculated values at

$$T_{total} = -1.35 \times 10^{-4} \Delta_S/^{o}C$$

The same holds for the reactivity coefficient of core height and the reactivity change per added fuel ball as well as for the pressure coefficient for nitrogen and the determination of the absorber rod worth. Reactivity changes due to recirculation of elements, an effect only to be found in a pebble-bed core, were registered and gave proof of the reproducibility of the core configuration. The pebble-bed core has an extremely stable reactivity characteristic which due to statistics can only improve in larger reactors. The fuel handling system including the pneumatic elevators performed extremely well during this first phase. Up till now more than 60,000 spheres have been circulated corresponding to several weeks of full power operation without major incidents.

The further programme for the AVR reactor foresees the approach to power by the middle of next year. The remaining time will be used to prepare the gas circuits for operation under 10 atmospheres of helium. From the power operation of the AVR one can expect further important results on the behavior of the system and for extrapolation to bigger units. This holds especially for the performance of so important components as the fuel elements, the gas circulators, the steam generator, gas purification, and the fuel handling system. The make-up charge will possibly consist of different fuel elements so that additional information on several types of fuel elements will be gained.

B. The THTR Project

The Thorium High Temperature Reactor Project - THTR - is the direct consequence of the knowledge gained and the encouraging results obtained during the development of the high temperature pebble-bed reactor concept, including the construction and operation of the AVR reactor.

The main objectives of the project are:

- to design a power reactor prototype and secondary steam circuit which is representative of a full scale power plant;
- to perform the necessary research and development programme for the advancement of high temperature pebble-bed thermal reactors utilizing the thorium-uranium cycle; and
- to gain operating experience by participating in the operation of the AVR reactor and furthermore to be responsible for the selection of the make-up and experimental fuel charges of the AVR.

EURATOM, Kernforschungsanlage Jülich, and Brown Boveri/Krupp entered into an association to accomplish this programme. When the association was founded in 1962 by the three partners it was planned to last a period of 5 years until the end of 1967. It can then be extended for the construction of the THTR prototype if the work performed and the results obtained justify such a decision.

Fig. 5 shows the general lay-out of the THTR prototype. A power of 300 MWe has been selected as a compromise between cost and the possibilities for extrapolation. As in the AVR reactor the pebble-bed core is of cylindrical shape and with a 30 $^{\circ}$ bottom cone.

Contrary to the AVR arrangement the cooling gas flows downwards inside the core thereby avoiding any limitations on power density which could arise from levitation of fuel spheres. The integrated system is housed in a prestressed concrete pressure vessel with an inner diameter of 15 m and an inner height of 18 m. In Table II data on the lay-out of the prototype are given.

Table II

General Lay-out Data of THTR Prototype

Electrical Power	300 MW
Thermal Power	750 MW
Average Power Density	6 MW/m^3
Core Diameter	5.6 m
Average Core Height	5.1 m
Number of Fuel Elements	675,000
Number of Absorber Rods	25
Cooling Gas Pressure	40 atm (a)
Primary Circuit Pressure Drop	1 atm (a)
Blower Power	6 x 1.7 MW
Core Inlet Temperature	270 °C
Core Outlet Temperature	750 °C
Number of Heat Exchangers	6
Steam Conditions:	
Pressure at Turbine	180 atm (a)
Temperature at Turbine	525 °C
Reheat Conditions:	
Pressure at Turbine	50 atm (a)
Temperature at Turbine	525 °C

Four possible fuel elements are presented in Fig. 6. Their outer diameter amounts again to 60 mm and all of them are provided with a fuel-free zone of about 10 mm thickness. The first of these elements has been discussed already. It has been furnished by Union Carbide Corporation for the AVR reactor and is characterised by a homogeneous distribution of fuel particles in the inner graphite matrix.

Type II, the so-called "hollow-sphere element" is similar to the Union Carbide element but has the advantage of lower central temperatures as the fuel particles are distributed on a spherical surface of about 40 mm diameter. This element has been developed by NUKEM, one of THTR's subcontractors for fuel element development, and may be used for the AVR make-up charge.

Type III, called "ring-gap" element, consists of a graphite sphere having a free space to house loose coated particles. The gap can be made wide enough to contain up to 15 g of heavy metal. This type of fuel element combines the advantage of easy reprocessibility with the disadvantage of higher fuel temperatures.

The most interesting variant for further development is the pressed element, type IV. Here, the particles are distributed similarly to type I in a graphite matrix, but the whole element is pressed semihydrostatically from graphite powder, a process particularly suited for mass production. The advantages of this element are: low production cost, good mechanical behavior and the possibility for higher heavy metal content than with any other variant.

There are two main points where the THTR concept differs markedly from that of the AVR reactor: absorber rods and the fuel handling system. In the AVR reactor absorber rods were inserted into an in-core graphite structure. For THTR due to the larger core diameter, a solution had to be taken which seems very specific for the pebble-bed core: the insertion of free control rods into the pebble bed itself without any in-core structure.

Fig. 7 shows photographs of an experimental control rod being dropped into a bed of 60 mm diameter graphite pebbles. Upon release this rod entered in about one second by its own weight of 500 kg more than 3 m deep. The total force required for insertion of the rod has been determined for different depths and at the same time the force excerted on the pebbles by the lower tip of the rod has been measured.

Extensive experiments have been conducted also with smaller models to study the influence of other parameters. It has been found that the required forces depend on friction between pebbles, the specific weight of the bed including its virtual increase by the pressure drop of the cooling gas and, to a less extent, on the total number of rods being introduced.

Much development work has been done to simplify the different components of the fuel handling system to achieve the higher circulation frequency of up to 500 balls per hour as compared to only about 50 balls per hour in AVR. Important components have already undergone long-term testing. Perhaps, one of the most interesting components of the fuel handling system is the burn-up measurement facility. With THTR burn-up of fuel elements will be determined by passing the fuel balls through a special zero power reactor and analysing the respective power signals as presented in Figure 8. Here, reactor power versus time is given for a pure graphite sample above and for the same sample plus 0.3 g U-235 below. These two signals correspond in a qualitative manner to signals from a new fuel ball and from a completely burnt-up fuel element.

The difference between both signals is easily measurable. The length of the signals, about 2/10 sec in this instance, corresponds to the time, the fuel element needs to pass through the burn-up measurement reactor and can be increased for greater accuracy. For further development of the method, a small zero power reactor is actually being installed in Jülich to go into operation some weeks from now.

The main problems connected to the step in development from the 15 MWe AVR reactor to the 300 MWe THTR prototype were

- the necessity for a pressure vessel of greater dimensions and for a higher cooling gas pressure,
  a problem common to all high temperature reactor projects and which is overcome by the progress in prestressed concrete pressure vessel construction, and, in addition, the more specific problems connected to the pebble-bed concept itself of

- the necessity for quicker circulation of fuel elements including burn-up measurement
- plus the need for a workable control rod concept not based on the solution for AVR.

These specific problems have been overcome

- by the development of a quick burn-up measurement by means of a critical facility and
- by the adoption of the free control rod concept.

The THTR project thus appears to rest on a sound technical basis and presents many interesting advantages as well as potential for further development.

C. Gas Turbines for High Temperature Reactors

Gas cooled high temperature reactors mean an important progress also because the temperature level attained by the cooling gas permits for the first time the direct coupling of a nuclear reactor with a gas turbine.

Because of the well known dependency of plant efficiency on turbine inlet temperature as given in Fig. 9 already at helium temperatures around 750 °C the plant efficiency is that of a modern steam cycle of 40 %. At 950 °C, a gas temperature that seems possible in the not too distant future, the efficiency goes up to 50 %.

In the last decade a number of fossil fueled gas turbine plants have been built. Some of those plants are now in operation for more than 50,000 hours. GHH has had a decisive share in the development and construction of such plants in Germany and during the past few years GHH has made some studies on the combination of gas-cooled high temperature reactors and gas turbines. The main object of these studies was the development of heat and power plants and ship propulsion units.

In this connection GHH carried out work for a 25 MWe closed-cycle gas turbine prototype plant utilizing a helium-cooled high temperature reactor. The project work on the prototype nuclear power station has meanwhile progressed to a point that design documents are available and tenders have been submitted for a power-station in Schleswig-Holstein, Germany.

Should a decision be taken to accept the GHH proposition, construction work could be started early next year and the plant could be put in operation about 4 years later.

The system is powered by a high temperature reactor similar in design to General Atomic's Peach Bottom facility with prismatic fuel elements. Characteristic lay-out data are given in Table III.

Table III

General Lay-out Data of GHH Gas-Turbine Prototype Plant

Reactor Thermal Power	66.6 MW
Power at Terminals	25 MWe
Power Density	7.5 MW/m^3
Number of Fuel Elements	624
Number of Absorber Rods	37
Equivalent Core Diameter	244 cm
Height of Active Core	190 cm
Reactor Inlet Temperature	425 °C
Reactor Outlet Temperature	740 °C
System Pressure	25 ata
Speed of Turbine	10,000 rpm
Number of Stages	
Turbine	8
LP/IP/HP Compressors	9/8/8

The heat exchanger design proposed for the prototype plant already has successfully been applied in conventional gas turbine plants built by GHH.

From the point of view of HTGR development in Germany a positive decision for the construction of a high temperature reactor coupled to a gas turbine would be very favourable for it is clear that this would bring about valuable information on the potential of HTGRs for better economy of the cycle with the result of lower energy cost.

IV. Economic Aspects and Further Possibilities

This brings us to the second part of our paper: economic aspects and further possibilities. The question is: what can we expect for the future from the high temperature reactor systems under development in Germany? To come back to the general theme of this meeting: this is the question of competitivity, in other words the question of cost per kilowatt hour (kWh) and as well all know the potential of a reactor system for conversion or breeding can have a strong bearing on the answer to these questions. The cost per kWh is made up of two parts:

- capital cost including fuel inventory and
- fuel costs.

While capital cost is responsible for between 60 and 70 % of total power generating cost, fuel costs make up for the resting 30 to 40 % and only 5 to 10 % of total power generating costs go into fuel fabrication.

A. Capital Cost

There seem to be two normal ways to reduce capital cost for power reactor systems: one is to go to bigger units. The other way is to use standardized equipment for a whole line of plant sizes and with growing experience to simplify the design in the direction of a more compact arrangement. Fig. 10 gives an example of this.. Here the concrete pressure vessels are presented for a 300, a 600 and a 1200 MWe pebble-bed reactor. It is rather surprising to see that for a power increase by a factor of 4 the outer volume of the concrete pressure vessel only increases by little more than a factor of two.

The horizontal sections in the lower half show that especially the arrangement of heat exchangers becomes more and more compact: for the 300 MW prototype they are designed to be exchangeable, for the 600 MW plant there are twice as much heat exchangers as penetrations so to exchange one of them in some cases two would have to be removed. For the 1200 MW plant sufficient experience is expected that heat exchangers can be made nonexchangeable.

The general tendency is the same for both reactors with pebble-type and prismatic fuel. The actual price estimates for capital cost per installed kW as given by GHH and Brown Boveri/Krupp are

135 to 150 Dollars/kW	for a plant size of about 600 MWe,
and approaching	
100 Dollars/kW	for a plant size of 1200 MWe.

There is still another way to decrease capital cost which is specific for high temperature reactor systems: the use of gas-turbines in the primary circuit instead of a secondary steam circuit with steam generator and steam turbine. It is obvious that the adoption of gas turbines will lead to an even more compact arrangement and the estimates are that this would result in a further considerable reduction in capital cost of up to 20 % for a plant of about 600 MWe. An additional advantage that may have a strong influence on site requirements seems to be the fact that for a reactor with a gas turbine cooling water consumption is reduced by a factor of 4 as compared to a reactor with a steam cycle. It seems important to note that plans for gas turbines are now available up to an output of 500 MWe.

B. Fuel Costs

Extensive calculations have been performed for the determination of fuel costs for pebble-bed reactors. Results are given in Table IV. Three different cycles have been considered: two once-through cycles with one type of fuel element only and uranium/thorium or low-enriched uranium as fuel and furthermore a feed-and-breed cycle with two types of fuel elements. The feed elements contain only fissile material and are used as once-through fuel while the breed elements contain mostly fertile material and only a small amount of fissile, corresponding to the equilibrium of Th-232 to U-233 and may be reprocessed.

TABLE IV

Fuel Cycle Costs for High Temperature Reactors with
Pebble Type Fuel Elements

Fuel Cycle	Element	U-235 Enrichment	Fuel U-235 g	Fuel U-238 g	Fuel Th-232 g	Residence Time	Plant Size MWe	Fuel Cost (mils/kWh) without Reprocessing	Fuel Cost (mils/kWh) with Reprocessing
once-through	feed	93 %	1.04	0.07	10.5	3.5 a	300	1.6	-
once-through	feed	7.6 %	0.65	7.9	-	2.0 a	300	1.4	-
feed-and-breed	feed	93 %	1.09	0.08	-	2.5 a	300	1.4	1.3
	breed		0.56	0.04	19.15	6.0 a + (4.0 a) ++	1200	–	≤ 1.0

+ without reprocessing
++ with reprocessing

The last figure given of less than one mil/kWh agrees well with the figures given by GHH for a 1000 MWe plant with prismatic fuel elements of 0.9 - 1.0 mils/kWh.

One reason for the low fuel costs with U/Th fuel is the fact that conversion ratios up to 0.8 can be achieved. For high temperature pebble-bed reactors considerable further savings in fuel costs are to be expected.

With the pressed element it seems now possible to increase the heavy metal content per fuel ball to 40 g or even more. This means that for every fueled ball two or more unfueled graphite balls could be used. Because of the much lower fabrication cost of unfueled balls and because for these balls an in-core residence time of up to 20 years seems feasible, a noteworthy reduction in fuel fabrication cost could be obtained. Additionally, the presence of unfueled balls in the core results in a higher degree of heterogeneity with the effect of lower neutron losses by resonance absorption in U-238 or Pa-233 respectively.

A still more interesting possibility for the realization of lower fuel costs is given by the use of beryllium in the core. A practicable solution for pebble-bed reactors would be the replacement of unfueled graphite balls by beryllium oxide balls. The use of beryllium as moderator material has two favourable effects on neutron economy:

1. Neutron leakage is reduced because of the higher moderating power of beryllium, and
2. the production of neutrons is increased by the (n,2n)-reaction.

While the expected gain by reduced neutron leakage is of the order of 1 %, the gain in neutrons as possible because of the fast fission factor for beryllium oxide may be as high as 5 %. The difficulty is that the value of the fast fission factor is not very exactly known, calculated values ranging from 1.035 to 1.10, the latest value by Zhezherun being given at 1.08. Because of the importance of this value for the further development of thorium reactors, experiments are actually conducted at Jülich. First results indicate that the fast fission factor is definitely higher than 1.05 and it seems possible that the value of 1.08 as given by Zhezherun may be verified.

Parallel to the (n,2n)-reaction takes place another reaction that is less favourable for neutron economy: an (n,α)-reaction producing Li^6 and which has a very high absorption cross section for thermal neutrons. Experiments indicate that at temperatures in the range of 1500 °C lithium can be driven out of beryllium oxide in a relatively short time.

In practice, a special feature of pebble-bed reactors can be made use of. Due to the continuous circulation of elements every fuel- or moderator-ball passes the fuel handling system after less than 6 months in the average. This means, that beryllium oxide balls could be separated and heated up to drive out lithium, before they are recycled through the core. Considering radiation damage of beryllium oxide a temperature cycle to 1500 °C would have the additional advantage of healing out some of the defects and thus admitting higher residence times. Taking into account the improvement in neutron economy to be expected for such an advanced high temperature thorium reactor, conversion factors up to and even greater than one seem possible.

V. Conclusion

To conclude we may say that of the two lines being followed of high temperature thermal reactor development in Germany each has its special merits and potential to lower power generating cost. As we have seen, the direct coupling of gas turbine and high temperature reactor can lower capital cost by a remarkable fraction and also fuel cost due to higher efficiency. The pebble-bed high temperature reactor on the other hand demonstrates an optimum flexibility for fuel management. Any high-temperature reactor fuel or moderator that can be accomodated into a 60 mm solid sphere can be used and fuel cycles can be changed continuously according to the demands of the fuel market.

The fact that the spherical elements automatically appear in the fuel handling system after less than 6 months greatly facilitates the regeneration of fuel as well as moderator, as for instance beryllium. This appears to be the best basis for the achievement of conversion factors up to and greater than one.

The question of how good a breeder can be made of it or – in other words – the question of doubling time, actually seems to be of less importance. This because at the high specific power possible with advanced high temperature thorium converters the amount of natural uranium necessary for the next 60 years appears to be lower than with any other converter reactor system and not higher than with fast breeders.

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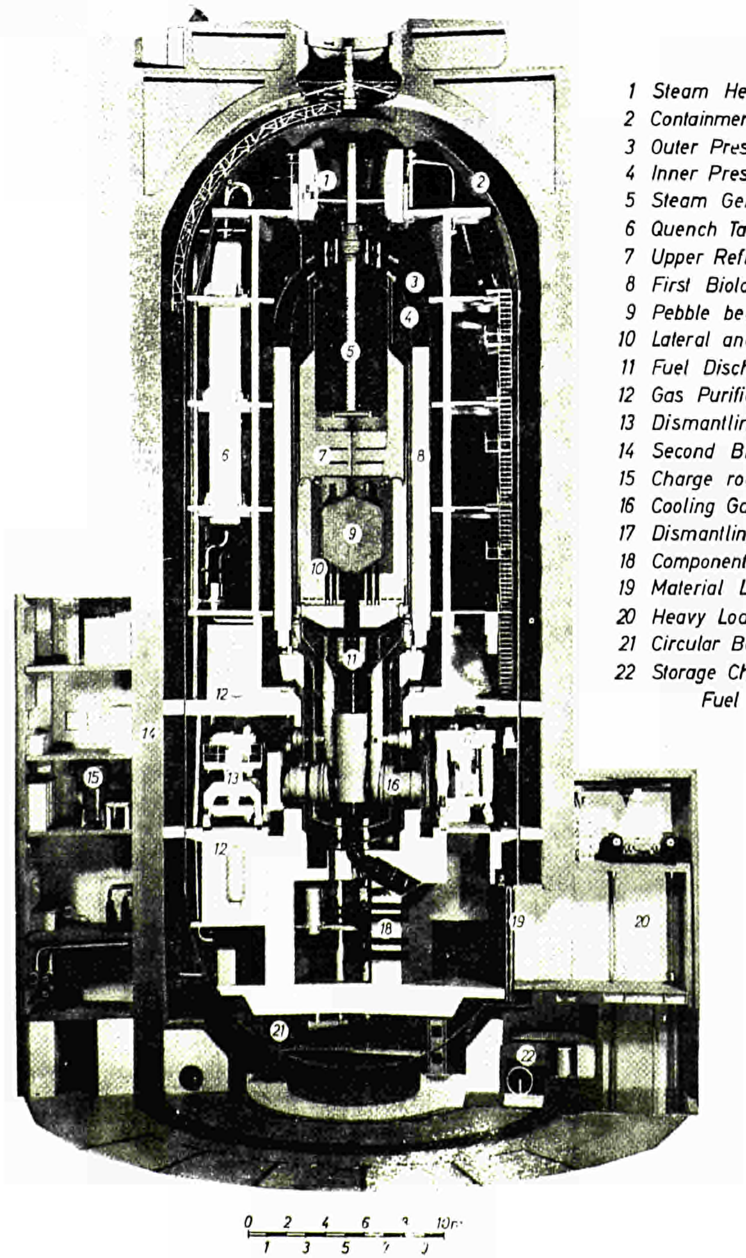
Fig.1

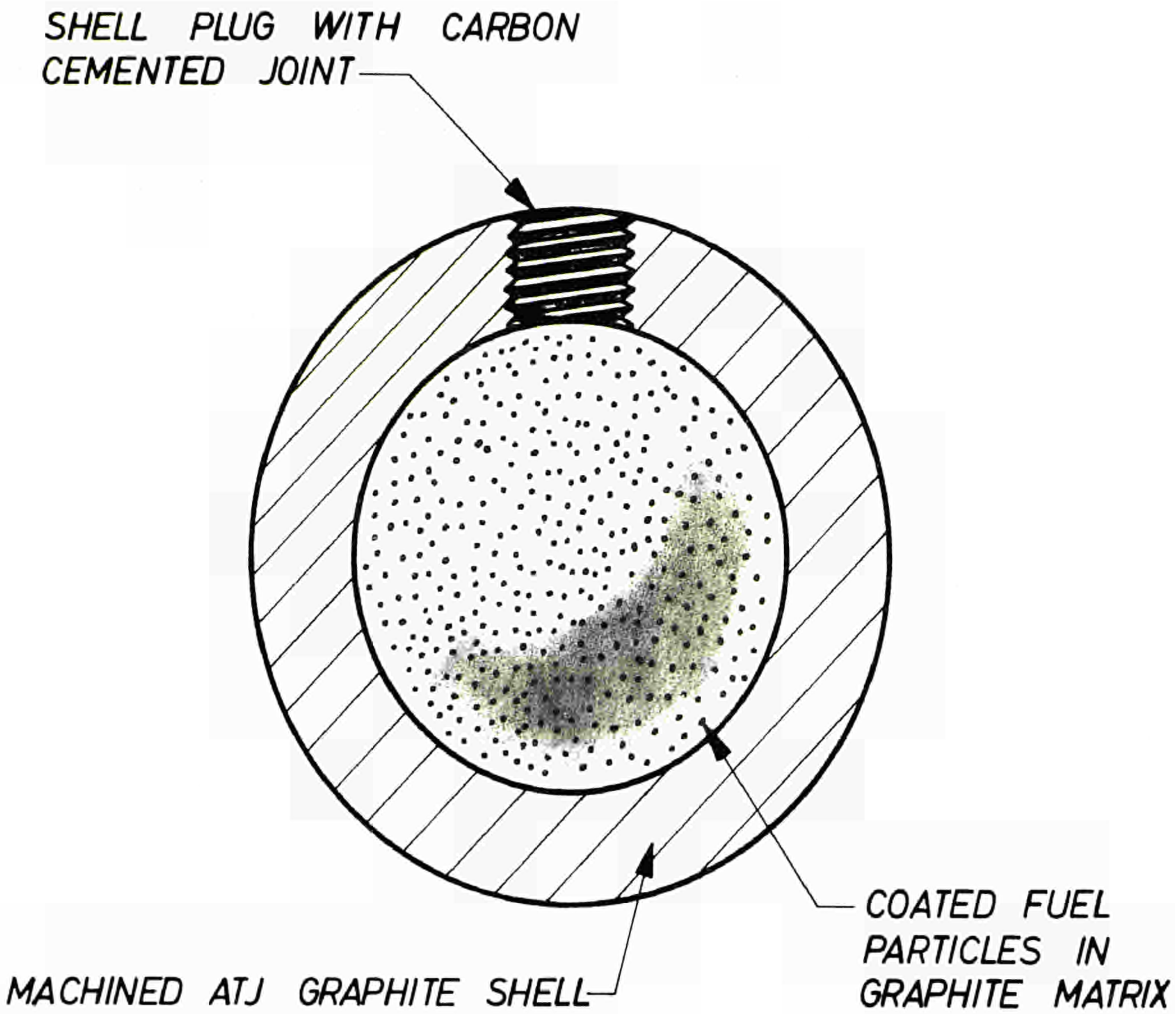


1 Steam Header
2 Containment
3 Outer Pressure Vessel
4 Inner Pressure Vessel
5 Steam Generator
6 Quench Tank
7 Upper Reflector
8 First Biological Shield
9 Pebble bed Core
10 Lateral and Bottom Reflector
11 Fuel Discharge Pipe
12 Gas Purification System
13 Dismantling Machinery
14 Second Biological Shield
15 Charge room for Fuel Elements
16 Cooling Gas Circulators
17 Dismantling Machinery for Circulators
18 Components of Fuel-handling System
19 Material Lock
20 Heavy Load Elevator
21 Circular Bottom Support
22 Storage Channel for Spent
Fuel Elements

Sectional View of
AVR - Reactor, Jülich

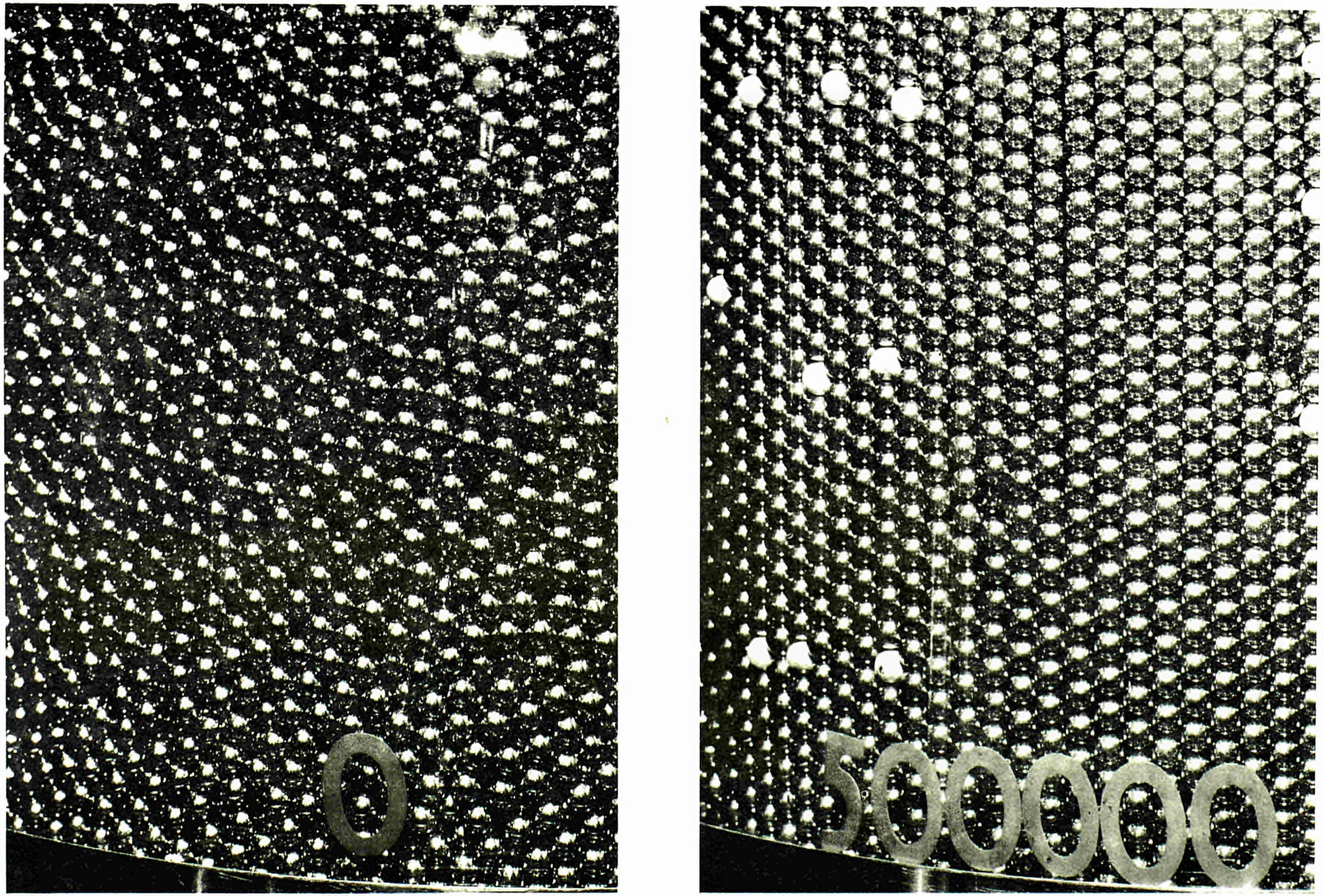
BBC/KRUPP

Fig.2

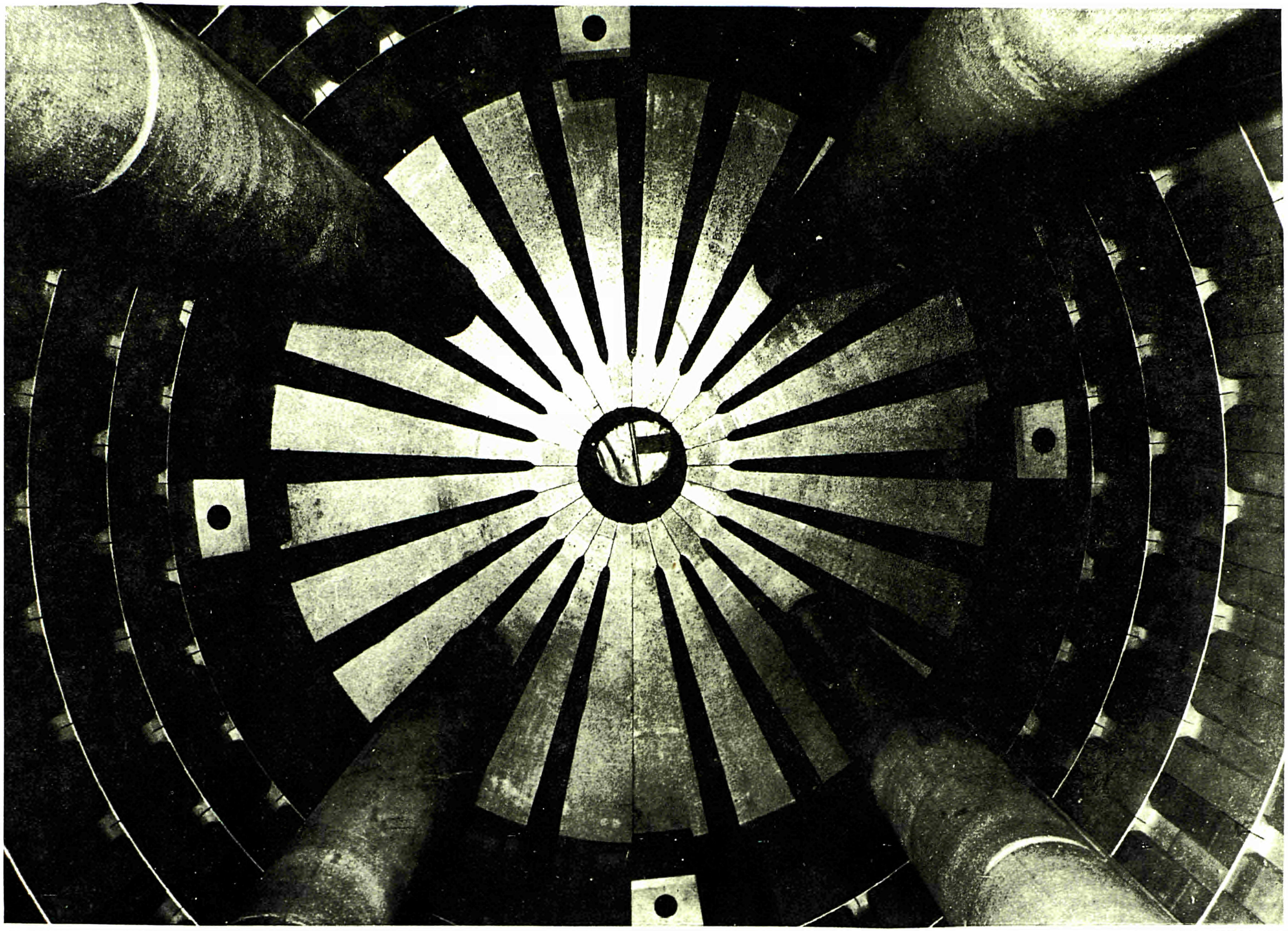


Section of AVR-Fuel-Element

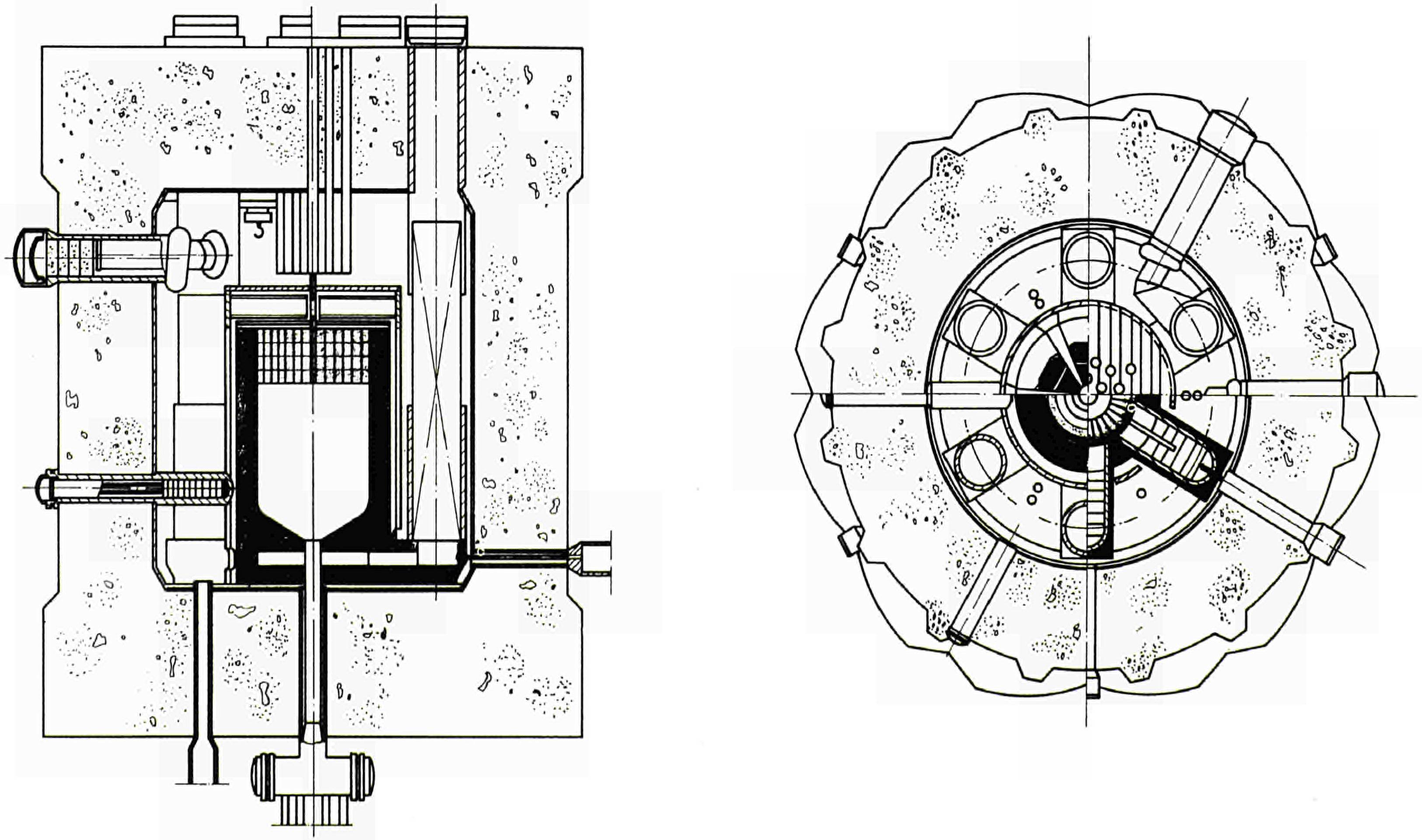
BBC / KRUPP



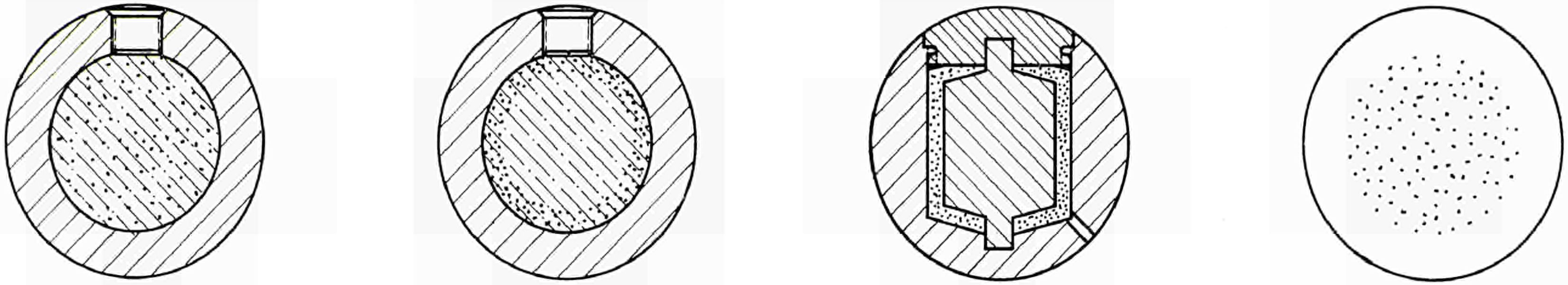
BBC/KRUPP	Pebble-bed before and after Circulation close to Cylindrical wall	Fig.3



BBC / KRUPP	View of AVR Top Reflector with grooved Cylindrical Walls	Fig. 4



BBC/KRUPP	General Lay-out of 300 MWe THTR Prototype	Fig. 5



Type I — UCC-Element

Type II — Hollow-Sphere Element

Type III — Ring-Gap Element

Type IV — Pressed Element

BBC/KRUPP	Fuel Element Types	Fig.6

Lower Tip of Rod Before Drop

After Drop into the Pebble Bed

BBC/KRUPP	Free Control Rod Experiment	Fig.7

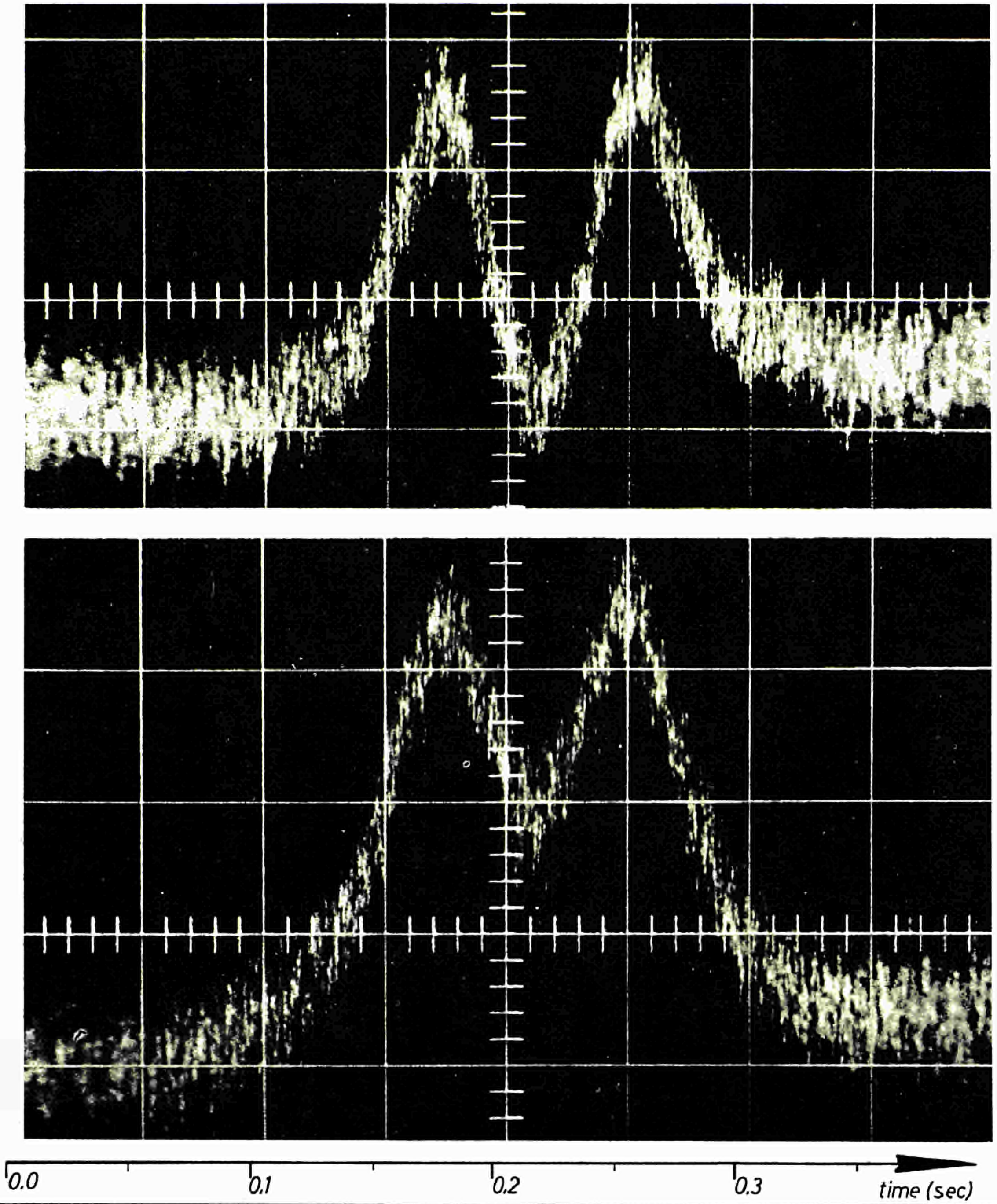


Fig.8

Dynamical measure=ments at Risø

Upper sample:

10.4g graphite

Lower sample:

0.33g U^{235}

0.79g Th^{232}

11.2 g graphite

BBC / KRUPP

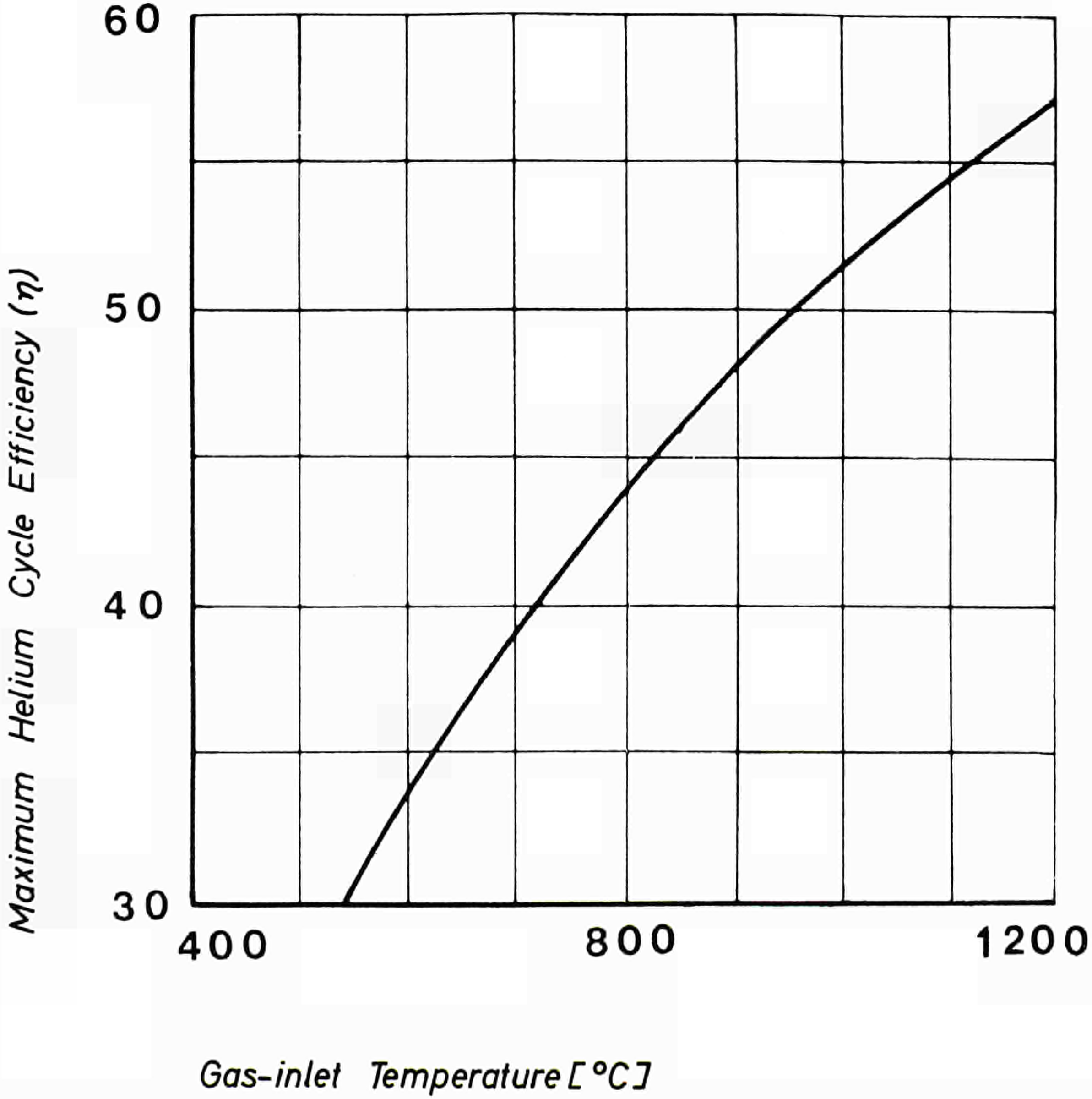
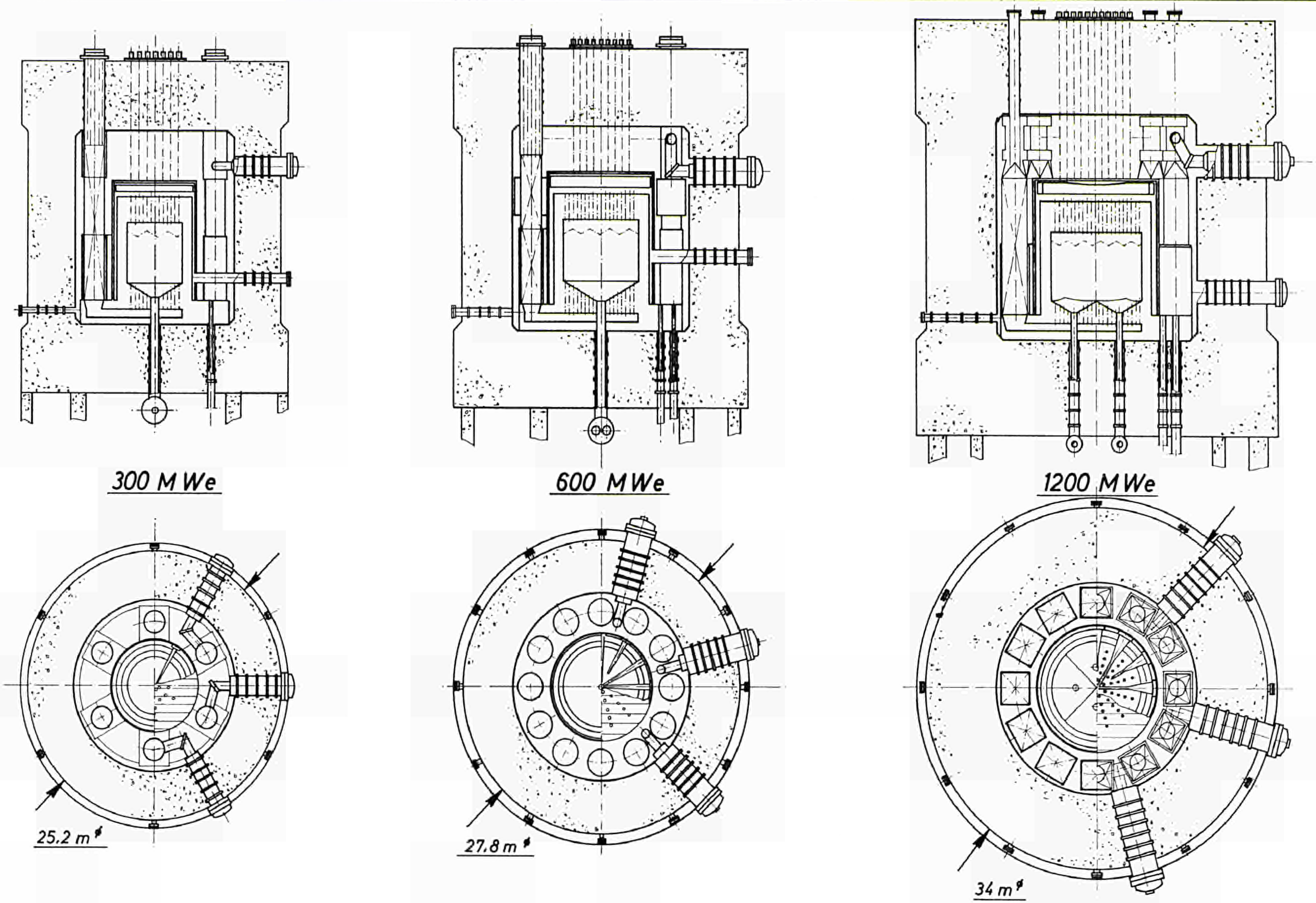


Fig.9

Maximum Helium Cycle Efficiency as Function of Turbine Inlet Temperature

BBC/ KRUPP



BBC/KRUPP	Comparison of General Lay-out for 300 MWe, 600 MWe and 1200 MWe Pebble-bed Reactor	Fig. 10

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To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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